DISCUSSION

Results of our study strongly suggest that how water within diked or created wetlands is managed may be of greater importance than the source of the water to the overall ecological health of these systems. While treated wastewater might be considered one of the richest potential sources of nutrients and contaminants to wetland and estuarine systems, dissolved oxygen and other water quality parameters did not suggest that areas managed with reclaimed water were more eutrophic than other hydrologically managed or unmanaged monitoring units. Concentrations of sediment contaminants and potentially problematic macronutrients such as nitrogen were actually comparatively low in reclaimed water units relative to other monitoring units. In fact, areas managed with muted tidal flushing (Muted Tidal) had the highest or second highest mean concentrations of total ammonia and nitrates in water and organic matter, organic and inorganic nitrogen (TKN), and ammonium in sediments. The highest concentrations of sediment nitrates and phosphorous were recorded in depressional areas that are flooded seasonally by precipitation, upland run-off, and, in some areas, creek overflow (Seasonal Pond). As for sediment contaminants, with a few exceptions, concentrations appeared to be highest in areas that were either managed passively through a one-way tide gate (Passive Hydrologic Management) or through muted tidal flushing (Muted Tidal). However, sediment contaminant concentrations cannot be strictly interpreted as reflective of hydrologic management, as sampling was limited, and results may be more reflective of site history.

This relationship between management and ecological status is supported on a gross scale by results of the cluster analyses incorporating biotic and abiotic variables monitored in the study. In general, hydrologically unmanaged areas (Undiked Marsh) separated from areas that were hydrologically managed, at least in the model without contaminants. Within managed areas, ponds that were perennially inundated grouped together, despite the fact that one is flooded with pumped groundwater, and the other, with reclaimed water. While the two Reclaimed Water monitoring sub-units (Management Units 1 and 3) were clustered together, these sub-units grouped closer to the adjacent passively managed “control” diked unit (MU2) -- which is not flooded with reclaimed water, but allowed to flood with precipitation and upland run-off and passively drain -- than with the other monitoring unit receiving reclaimed water (Ringstrom Bay). Clustering of the four differently managed monitoring units in or around the Hudeman Slough Enhancement Wetland area does suggest that geographic proximity and site history strongly influenced results, as well. Re-classification of the hydrologically unmanaged areas with most of the hydrologically managed areas in the cluster analysis model that incorporated contaminants may relate to the generally low to moderate contaminant concentrations observed in the Undiked Marsh and Reclaimed Water monitoring units. However, the continued inclusion in this realigned group of MU2 with its higher contaminant concentrations is harder to explain.

Obviously, water source does play some role. For instance, in the late fall and spring of 2000, pulses of nitrates were detected in waters of monitoring units that were either fully tidal (Undiked Marsh) or muted tidal (Muted Tidal; Reclaimed Water + Muted Tidal), with levels in fall 2000 reaching as high as 25 mg/L. As the fall pulse just preceded the beginning of the discharge season for sewage treatment plants, it would appear that the source of this influx may lie elsewhere. The most likely contributor would be creek flow and upland run-off from the predominantly agricultural watershed. While vineyards typically use nitrogen fertilization somewhat sparingly, a number of beef and dairy cattle operations are also present within most of the creek watersheds, specifically Hudeman and Huichica creeks. Nitrogen concentrations in watersheds with beef and dairy operations often increase significantly after the first few rainfall events due to run-off of manure into creeks.

Certainly, the strongest evidence of a link between re-use of treated wastewater and possible nutrient loading may be the elevated concentrations of dissolved phosphates in units receiving reclaimed water. Dissolved phosphates were only detected in monitoring units flooded with reclaimed water. During the season in which monitoring units are actively flooded with reclaimed water, dissolved phosphates were present at concentrations well below the average concentration of the treatment plant effluent, suggesting that these monitoring units may be acting as a sink. Flocculation of dissolved phosphates and incorporation into the sediment may be favored, at least slightly, over immediate uptake by biota by the fact that waters in areas receiving the non-saline reclaimed water are slightly saline (1-5 ppt), thereby creating a small-scale "entrapment zone." Further evidence for this comes from the fact that dissolved phosphates were detected even during a season (spring 2000) when the units were not actively flooded with reclaimed water. Nocturnal anoxic events or strong stratification within the water column may enable solubilized phosphate within the sediment to release periodically into overlying waters. However, this scenario is contradicted somewhat by the sediment phosphorous data. While mean sediment phosphorous concentrations were comparatively high in the Reclaimed Water + Muted Tidal monitoring unit, phosphorous levels in the Reclaimed Water monitoring unit remained moderate and similar to those in the Muted Tidal and Undiked Marsh monitoring units, suggesting that either the reclamation storage reservoirs or the monitoring units themselves may be acting as a sink. Furthermore, phosphorous concentrations in the Reclaimed Water and most of the other monitoring units showed almost no variation between seasons, thereby discounting the possibility that concentrations could increase substantially after flooding with reclaimed water and then drop once phosphorous within sediments was solubilized and released to surface waters.

While source remains a factor, the relationship between the way the water is managed and health of managed and/or created wetland ecosystems appears even stronger. In some cases, evidence of this connection is easy to discern. For example, during summer 2000, construction on the effluent transmission pipeline prohibited managers from keeping permanently inundated ponds within some of the reclaimed water monitoring sub-units filled, leading to at least one fish kill event and the only instance during the study in which unionized ammonia exceeded Basin Plan maximums. Unionized ammonia becomes problematic at higher concentrations of total ammonia when pH and temperature is elevated. Interestingly, as noted in Results, concentrations of total ammonia within treatment plant effluent is quite low ($\bar{x}$=0.36±0.02 mg/L) and actually below that observed in waters of the Reclaimed Water monitoring unit ($\bar{x}$=1.11±0.19 mg/L). The SVTP has incorporated additional processes that nitrify ammonia to less than 1 mg/L and partially denitrify nitrate to less than 10-12 mg/L (Jim Zambenini, manager, SVTP, *pers. comm.*). Therefore, biotic processes within the Reclaimed Water monitoring unit appear to be increasing total ammonia concentrations relative to the effluent. While the concentrations of total ammonia within pond waters may not have been problematic generally, the construction-related pond dewatering may have acted to increase ammonia concentration and/or temperature within the very shallow waters, thereby producing higher than normal unionized ammonia concentrations. This appeared to be an isolated incident, but it suggests that water levels and dewatering activities within diked units and other managed wetlands need to be managed carefully to avoid unintended ecological consequences.

In other instances, the connection between management and ecosystem health is perhaps less obvious. During fall 2000, a large fish kill event occurred in one of the reclaimed water monitoring sub-units shortly after being flooded with reclaimed water. All of the monitoring sub-units had been mowed shortly before being flooded for mosquito control and waterfowl habitat management purposes, but, because of the construction activities, water levels within this particular monitoring sub-unit were at least 0.5 m to 1 m higher than normal (L. Parsons and J. Martini-Lamb, *pers. obs.*). During this period, unusually large amounts of mowed plant fragments were observed floating in the water (L. Parsons, *pers. obs.*), which suggests that anoxia and the associated fish kill event may have been precipitated by the increased oxygen demand of the newly created detritus. Numerous studies have linked hypoxia and anoxia within estuaries and coastal waters with influxes of nutrients and organic matter (Clark and Jaworski 1972; Morris et al. 1978; Polak and Haffner 1978; Lee and Olsen 1985), including flooding-related suspension of wetland organic matter (Portnoy 1991). Rapid turnover of the short-lived species that dominate many of the diked areas, combined with frequent mowing in reclaimed water areas, may account to a large degree for the elevated DOC concentrations that were recorded in all hydrologically managed units. This DOC represents not only an abundant source of carbon available for transport to the Bay, at least for systems with a tidal connection, but also potentially an abundant substrate for bacteria that could dramatically increase oxygen demand and induce hypoxia/anoxia. Within MU1, the anoxia not only killed fish, but dramatically reduced zooplankton abundance. Mean zooplankton densities in the sub-unit dropped from 91,789.6±31,450.8 individuals per cubic meter of water in November 1999 to 190.3±20.9 individuals in November 2000. Meanwhile, a similar sub-unit (MU3) that did not experience anoxia posted mean zooplankton densities in November 2000 of 47,100.7±7,948.6 individuals per cubic meter of water. Despite decreased zooplankton abundance, bird use remained relatively high, probably because water depths encouraged use by primarily waterfowl species that feed on, among other items, plant fragments and loose seeds.

Perhaps, the most dramatic problem observed in hydrologically managed areas was acidification. As noted in Results, certain sampling locations in areas managed either passively or through muted tidal flushing underwent short-lived or extended episodes of extremely low water pH, with pH plummeting as low as 2.59. A similar phenomenon has been documented in a number of diked salt marshes and other types of wetlands, including in the Netherlands, the United Kingdom, Australia, the eastern United States, and other areas in the San Pablo Bay portion of San Francisco Bay (Gosling and Baker 1980; Madrone Associates et al. 1983; Soukup and Portnoy 1986; Vranken et al. 1990; de Jong et al. 1994; Portnoy and Valiela 1997; Portnoy and Giblin 1997; Anisfeld and Benoit 1997; Sommer and Horwitz 2001). In general, in salt marshes this acidification has been linked to reduction of tidal surface flows through construction of tide gates or even dams, leading to periods of drying and subsequent oxidation of saline soils or hydrologic "disconnection" with tidal areas outside of levees (Gosling and Baker 1980; Soukup and Portnoy 1986; Vranken et al. 1990; de Jong et al. 1994; Portnoy and Valiela 1997; Portnoy and Giblin 1997; Anisfeld and Benoit 1997). Acidification is particularly evident when oxidized areas are re-flooded through muted tidal flow, a rising water table, or ponding of rainfall and run-off (Gosling and Baker 1980; Anisfeld and Benoit 1997). Within the Study Area, acidification episodes corresponded to periods when certain sampling locations were either hydrologically disconnected, were only weakly connected, or had just been "reconnected" after a prolonged period of desiccation. For example, in the Muted Tidal monitoring unit, prolonged acidification coincided with intentional dewatering for construction associated with a wetland enhancement project. Once flushing with carbonate-rich tidal flows was reintroduced, pHs approached neutral, although not for one of the sub-units that is furthest from a tide gate and remains consistently disconnected or only weakly connected.

While not perhaps the primary determinant of zooplankton abundance, low pH appeared to substantially influence zooplankton densities. In one of the shallowly flooded panne areas, zooplankton densities climbed from 104.7 individuals per cubic meter of water during a period with extremely low water pH (3.5) to 107,753.5 individuals during a period with near neutral water pHs (7.5). Similar trends were observed in most of the other sampling locations, although a few sites supported high zooplankton numbers even when waters were acidic. A metadata analysis of acidity and zooplankton abundance in southeastern Canadian lakes indicated that damage to freshwater aquatic biota occurred below a pH of 6 (Doka et al. 1997). Other studies have shown changes in macroinvertebrate richness, trophic structure, and/or community composition following acidification events (Rundle and Attrill 1995; Dangles and Guerold 2000; Sommer and Horwitz 2001). It should be noted that acidification episodes within these areas coincided with periods of extremely low bird use. Most of the species that would utilize these type of shallowly flooded areas are shorebirds, and in addition to probing for benthic invertebrates, certain shorebird species forage on zooplankton in the water column as well. For example, during November 1999, only two bird species were observed within the Muted Tidal unit, greater yellowlegs (*Tringa melanoleuca*, six individuals) and savanna sparrow (*Passerculus sandwichensis*, one individual). Similar observations were made during other acidification episodes.

These acidification episodes often cause other problems. Researchers in diked systems have noted that reintroduction of flow to diked areas is often accompanied by pulses in nutrients, because of accelerated decomposition of organic matter within the previously oxidized or desiccated sediment (Delaune and Smith 1985; Anisfeld and Benoit 1997; Portnoy and Giblin 1997). These nutrient pulses, particularly of ammonium, have even been observed in some of Australia's pyrite-rich freshwater wetlands that have been subjected to drought-induced acidification (Sommer and Horwitz 2001). Within the Muted Tidal monitoring unit, ammonium concentrations in the sediment remained consistently high throughout the time that it was sampled (May 2000 – November 2000), ranging from 2.7-5.7 mg/L. Some of that ammonium may have been released into overlying waters when hydrologic connectivity improved or was reestablished, because total ammonia concentrations in the water peaked when water pHs in many sampling locations were very low. During acidification episodes, total ammonia ranged in one Muted Tidal monitoring sub-unit from as high 17 (January 2001) to 23 (November 2000) mg/L. The low pH apparently inhibited nitrification of ammonium to nitrates. This same type of nutrient pulse was observed to a much lesser degree in other monitoring units during periods when soils became oxidized. For example, both the Reclaimed Water and Reclaimed Water + Muted monitoring units displayed slight increases in nitrates during the summer (August 2000):

the more moderate pHs in these monitoring units probably encouraged nitrification of ammonium produced by oxidation of organic matter. Interestingly, while the Muted Tidal monitoring unit generally supported very little vegetation (mean cover=30 percent), it had the highest percentage of organic matter (OM) and concentrations of organic and inorganic nitrogen (TKN) within the sediment of any of the monitoring units. Decomposition of the sparse organic material produced in this unit has probably been inhibited, at least historically, by reduced conditions in the frequently flooded soils.

In fact, the sparse vegetation cover, in and of itself, may stem from frequent acidification episodes. In many tidal salt marshes, large expanses of barren or extremely sparsely vegetated flats often result from hypersaline conditions (salt pannes) or prolonged inundation of depressional or low-elevation areas. Within some of the diked monitoring units, panne or unvegetated areas have probably developed because of the extended duration of flooding, both from tidal flushing and/or freshwater, including reclaimed water. However, in areas where low water and interstitial soil pH has been observed, vegetation recruitment may have been largely precluded by acidity produced by oxidation of iron-sulfur compounds such as pyrites to sulfate, sulfuric acid, and dissolved ferrous iron and the subsequent oxidation of dissolved ferrous iron to ferric iron. Many of these low pH areas are characterized by red-colored water and bright red soils from the heavy deposits of ferric iron precipitate (Gosling and Baker 1980; Soukup and Portnoy 1986; de Jong et al. 1994), leading to the creation of what might be termed “iron” or “ochre” pannes rather than the traditional salt-encrusted “salt” pannes. Other studies have shown that acidification of soils from frequent oxidation of sulfides to sulfuric acid can create vegetation breaks or bare patches, particularly in inland portions or higher elevations of salt marshes (Cooper 1974).

In addition to nutrients, acidification can also cause pulses of normally sediment-bound metals into the water column. This solubilization of metals constitutes a much more serious problem than large influxes of ammonia, particularly in San Pablo Bay, which is know to have had high historic deposition rates of metals into wetland areas before they were diked (San Francisco Estuary Project (SFEP) 1992). Various studies in other wetland systems with acidification episodes have documented releases of a variety of metals, including silver, aluminum, cadmium, chromium, copper, iron, manganese, nickel, lead, selenium, and zinc (Delaune and Smith 1985; Soukup and Portnoy 1986; Gambrell et al. 1991; Peverly and Kopka 1991; Satawathananont et al. 1991; Gambrell 1994; Anisfeld and Benoit 1997). Oxidation in and of itself does not necessarily lead to release of metals, because processes immobilizing metals tend to be complimentary such that large-scale metal releases do not occur with changing redox conditions (Gambrell 1994). Sediment contaminant sampling in monitoring units indicates that metal concentrations, at least in surficial sediments, remain generally lower than some of the San Pablo Bay subtidal and undiked tidal marsh locations sampled in conjunction with the RMP, with the exception of, perhaps, silver. Mean concentrations of silver, arsenic, and nickel did exceed ambient, ERL, or ERM criteria in certain units that were either fully or muted tidal or passively managed.

Based on water samples collected in areas with low, moderate, and high pH, it appears that acidification was accompanied by pulses of aluminum, dissolved and total iron, manganese, nickel, and zinc. Concentrations of some of these metals, specifically copper, nickel, and zinc, reached high levels during these periods and exceeded the four-day saltwater criteria established by the California Toxics Rule (U.S. EPA 2000). Concentrations of nickel, in particular, which ranged from 40 to 800 ppb, greatly exceeded the 4-day saltwater criteria of 8 ppb in all low pH sampling locations. Solubilization of metals may explain the higher degree of amphipod mortality observed in samples where pH dropped precipitously during sediment bioassay testing: survival increased substantially when tests were re-run on pH-adjusted sediment and overlying waters. The decreased amphipod survival reported for one of the sampling locations (MU2 BD) after pH adjustment may result from mobilization under more moderate pH conditions of a polar contaminant that becomes less polar as pH increases (Pacific Eco-Risk Laboratory 2001). Leaching of metals into creeks following heavy rain events has been linked to fish kills in areas near acid mine tailings (Horne 2000). Acid-mobilized aluminum was implicated in large-scale die-offs of American eels and juvenile herring on the lower Herring River in Massachusetts in 1980 and previous years (Soukup and Portnoy 1986). In low pH conditions, metals are present in the free ionic form, which is the most toxic to fish and other wildlife (Horne 2000). Some of the released metals may be uptaken by plants into leaves, stems, and seeds, with the highest concentration often found in roots and seeds (Lee et al. 1980; Horne 2000). As seeds represent a primary food source for many types of wildlife, particularly waterfowl, the consequences of metal solubilization may be severe for the species that these managed wetlands are designed to target.

Oxidation of soils in diked areas does not automatically lead to acidification and pulses of nutrients and metals. In fully tidal or areas that are frequently flooded with tidal waters, acidity can be countered by carbonate-rich sea or river water exchange with the sediment. However, in diked areas, particularly ones with highly organic soils, sources of alkalinity such as bicarbonate and calcium carbonates may be naturally low and/or depleted by the amount of acids produced through oxidation (Gosling and Baker 1980; Vranken et al. 1990; de Jong et al. 1994; Portnoy and Valiela 1997; Anisfeld and Benoit 1997). If bicarbonate and calcium carbonate concentrations can be consistently maintained within diked areas, any acidification produced within sediment during periods of oxidation can be neutralized, thereby sustaining near neutral pHs in overlying waters. Some variation of this process may have occurred during November 1999 in two of the Reclaimed Water monitoring sub-units, when interstitial pore water pH within the sediment of unflooded areas dropped as low as 4.21-4.71. However, acidic water pHs were never observed in either of these sub-units, with pHs typically ranging from 6.7 to 9.3. In carbonate-rich areas, it is possible that, even if solubilized metals are initially flushed from low pH sediments into waters by re-introduction of tidal flushing or freshwater flooding, metals would quickly become insoluble again through precipitation under near neutral pH conditions. This immediate “re-precipitation” would at least decrease the extent of time in which these metals are available for uptake by emergent vegetation and aquatic organisms. Using radiotracers on metals found in secondary-level treated wastewater, Gregg and Horne (1993) demonstrated that the typical conditions found in wetlands (i.e., reducing and circumneutral) convert soluble metals to precipitates within only a few hours. Trace metals can also bind to dissolved organic material such as dissolved organic carbon (DOC), which is typically high in wetland environments.

Potential problems with remobilization could raise serious concerns given the strong affinity of wetland sediments for contaminants and San Pablo Bay’s historically high contaminant deposition rate (SFEP 1992). Not only are heavy metals typically immobilized within reduced soils, but pesticides and PAHs are often complexed with the humic acids present in the peaty, organic matter layer present (A. Horne, *pers. comm.*). Concentrations of metals and other contaminants in hydrologically managed areas appear to be principally related to historic deposition of contaminants, with a small percentage perhaps originating from recent introductions, including upland run-off, creek flow, re-suspension of contaminant-containing sediments in channels and ditches, and flooding with reclaimed water. For example, PCBs are relatively recently introduced contaminants and could not pre-date diking, at least for most of these areas. With the possible exception of undiked areas, then, the pulses observed in the three sediment contaminant sampling dates probably largely relate to large spatial variability in contaminant concentrations rather than new influxes of contaminants.

The elevated concentrations of many of the contaminants, particularly the metals, in the Passive Hydrologic Management monitoring unit (MU2) may relate specifically to this area's recent diking history. It was diked after 1951 and possibly as late as the 1970s-1980s. While the adjacent MU3 was technically not diked before the 1970s-1980s either, the area remains distant enough from Hudeman Slough to suggest that introduction of contaminants via tidal sources was minimal, at best. Meanwhile, the other adjacent management unit, MU1, was diked prior to 1951. During the middle part of the 20th century, pollution within San Francisco Bay increased greatly, as new pesticides and other compounds were introduced and subsequently made their way into the rivers and estuaries (SFEP 1992). After MU2 was diked, new introductions of contaminants to tidal and river water flow from point sources such as industrial, agricultural, and municipal sewer sources are believed to have decreased substantially due to implementation of water quality regulations, although resuspension of historically deposited contaminants in subtidal and intertidal sediments continued. The decrease in point source contaminant influxes might explain why contaminants in the Undiked Marsh were lower than some of the hydrologically managed diked areas, particularly MU2: cleaner sediments may have buried some of the more contaminated soils. This same phenomenon might explain why contaminants were higher in the secondary borrow ditch than in the old slough trace in MU2: excavation of the borrow ditch may have tapped into a horizon with higher contaminant levels than were present in the surface sediments when the Management Unit, and the old slough, were diked. Also, the secondary borrow ditch sampling location is closer to Hudeman Slough than the other sampling location, and, therefore, contaminant concentrations might be expected to be higher in areas near large sloughs.

The strong immobilization of sediment contaminants under typical wetland conditions, coupled with other factors, suggest that, in general, the benthic community may be restricted more by the very anoxic nature of the frequently flooded dense clay soils than by contamination. While low abundance and species richness often point to impacted conditions, numbers of individuals and species were universally low within all monitoring units, including the Undiked Marsh sampling areas, where densities and diversity might be expected to be high. Even in monitoring units such as Reclaimed Water where comparatively high numbers of contamination tolerant species such as Tubificidae or blood worms were present, contamination intolerant species were also found (e.g., the amphipod, *Hyallela azteca*). High numbers of Tubificids also occurred in certain Undiked Marsh sampling locations, suggesting that the presence of this oligochaete may be more related to the hypoxic conditions present in the clay substrate than contamination. The mean percentage of fines within many of these areas ranged from 27 to 93 percent, with clay particles averaging approximately 20 percent (Technical Appendices, Section I). The categorization of Tubificidae as common and abundant in most estuarine benthic assemblages, impacted or not (Lowe and Thompson 1999), seems to support this conclusion. In addition, another contamination tolerant taxa, Chironomidae, that is associated with freshwater conditions was observed in the Reclaimed Water + Muted Tidal and Muted Tidal monitoring units, but not in the Reclaimed Water unit, despite the fact salinities are much higher in the former than the latter. These contradictory findings suggest that factors other than contamination are probably playing a larger role in the very low densities and species richness, as well as the community composition, of benthic invertebrates observed within monitoring units.

The food chain, then, within the monitoring units would appear to be strongly driven by organisms within the water column rather than those in the sediment. Zooplankton densities were generally high, particularly in hydrologically managed monitoring units. Not surprisingly, monitoring units with more frequent episodes of eutrophic conditions usually had the highest zooplankton densities (e.g., Reclaimed Water, Reclaimed Water + Muted Tidal, Muted Tidal, and Groundwater Pond). However, productivity may also be enhanced by hydrologic complexity. Some of the highest, if not the highest, zooplankton densities, species richness, and species diversity occurred in the Reclaimed Water + Muted Tidal monitoring unit, which alternates muted tidal flushing and freshwater flooding with reclaimed water, precipitation, and upland run-off. The zooplankton community in this monitoring unit represented a complex mixture of freshwater and tidal taxa. While avian monitoring was not specifically conducted on ponded mudflats, observation suggested that bird use of this area was high, particularly by shorebirds and dabbling ducks that would be likely to be foraging on organisms in the water column, as well as in the substrate.

In general, results of avian monitoring appear to suggest that water depths, not water source, is still the predominant factor driving waterbird species richness and density. In Open Water habitats, waterbird species richness, diversity, and densities in the Reclaimed Water units were comparable to or exceeded those found in the Seasonal Pond units for the entire monitoring study. No significant differences in waterbird species richness, diversity, and densities were detected between Reclaimed Water and Muted Tidal flooded wetland habitats during the monitoring study. The Reclaimed Water + Muted Tidal unit had fewer birds and less diversity than the Reclaimed Water and Muted Tidal units during the study, most likely as a result of the denser vegetation within this unit. However, seasonal variations in species richness and densities suggest that water management was important. The highest mean waterbird species richness and densities during the November-April and May-August study periods occurred in one of the Reclaimed Water monitoring units (MU3) and was probably correlated with the greater water depths and vegetative cover present in this area. This argument is supported by waterbird density results of the November-April study period. During September-October, the dominant forage guild observed in one of the Reclaimed Water monitoring units was dabblers, but in November-April, the dominant forage guild was shallow probers then followed by dabblers. Water depths tend to be shallower during the November-April study period than the September-October period, when the Reclaimed Water monitoring units are being actively flooded with reclaimed water.

Water depths also appear to account for differences between the Reclaimed Water and Muted Tidal monitoring units. While these monitoring units were similar in terms of mean waterbird species richness and densities, there were differences in mean foraging guild species richness and densities. Reclaimed Water monitoring units tended to be flooded to a greater depth than the Muted Tidal units, thereby providing more habitat for dabblers than shallow or deep probers. Shallow and deep probers were the dominant waterbird foraging guilds observed within the Muted Tidal monitoring unit, probably due to the shallower water depths.

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CONCLUSIONS

In designing or managing wetland enhancement, restoration, or creation projects, consideration and management of the hydrologic regime appears to be as important, if not more important, than water source. Even use of such potentially problematic sources such as reclaimed wastewater may play a smaller role in overall ecosystem health than the way the water is managed. Use of reclaimed water did not produce levels of eutrophication or contaminant loading in sediments within enhanced or created wetlands that were any higher than those managed with other types of water sources, such as tidal flushing or groundwater. In fact, in some cases, concentrations of pollutants such as sediment contaminants were actually much lower. As for the water quality-related problems that have plagued other reclaimed water wetland projects, most did not appear to be issues, at least currently, at the Hudeman Slough Enhancement Wetlands. The problems that were observed such as the one-time spike in unionized ammonia, episodic anoxic or hypoxic events resulting in fish kills, and possible sediment loading and subsequent remobilization of phosphates, could perhaps be eliminated entirely by careful hydrologic management.

However, the most critical consequence of poor hydrological management remains the potential for release of normally sediment-bound contaminants such as trace metals and perhaps even organics. Our results support findings by numerous other researchers who documented pulses of trace metals in areas with high concentrations of sulfides and pyrites and low sediment and water pH. These metals are then possibly available for uptake by plants or aquatic biota, if sources of alkalinity within the overlying or reintroduced waters are insufficient to neutralize the acidity and allow metals to re-precipitate or complex with other reactive materials. The possible ecological consequences of such leaching are serious enough that some researchers (Soukup and Portnoy 1986, Portnoy 1991) have argued that they warrant removal of dike systems altogether. However, the adjacency of many of these managed systems to densely populated areas would probably preclude large-scale breaching efforts. In these systems, the only way to improve acid sulfate soils and the potential water quality problems associated with desiccation or oxidation may be through proper water management (Bronswijk et al. 1993). Hydrologic management within these diked areas needs to ensure that wetlands remain hydrologically connected, even if only through subsurface flow. If possible, hydrologic regimes should also take into account the need for consistent or at least seasonal sources of alkalinity such as carbonate-rich seawater or even reclaimed water to counter acidity produced during periods of oxidation.

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